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Upsilon and χ_b analyses at CLEO

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I detail recent work done by the CLEO collaboration using data gathered at the CESR accelerator concerning the Υ system. Results include B_S production at the $\Upsilon(5S)$, decays of the $\Upsilon(nS)$ (n=1,2,3) to τ pairs, the Υ di-electron width, decays of the Υ to two hadrons and a photon, and the observation of the first di-pion transition between χ_B states

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1. The Υ System

The $\Upsilon(nS)$ system, a bound state of a b and $\overline{b}$ quark, is produced in the CLEO detector in collisions of electrons and positrons from the CESR accelerator. When $n \geq 4$ the state decays to B mesons. For $n < 4$, below B meson threshold, the two quarks must annihilate to produce non-B final states. These annihilations are mediated either by a virtual photon, the exchange of two gluons, or the radiation of one photon and emission of a photon. These states can also transition to other $n^{2s+1}L_J$ states via emission of, eg, a photon or two pions. These other states are the QCD analog of positronium. Since the b quark is quite heavy, non-relativistic quantum mechanics can be used to understand the spectroscopy and dynamics. It is interesting to note that the catalogue of final states is incompletely known - for instance in the case of the $\Upsilon(1S)$ less than 10% of all final states are measured [1]. The Υ system also supplies a laboratory to study b quarks in a setting different from B meson decays. For instance, one's confidence in Lattice QCD (LQCD) as applied to the extraction of CKM matrix elements in B meson decays, would be boosted if LQCD's prediction of the Υ system were in line with experimental results.

2. The CLEO III Detector and Data Sample

The CLEO III detector[2] provides particle measurements over a large solid angle. This detector, in a 1.5 T magnetic field, includes a silicon tracker, and a drift chamber for charged particle detection, as well as dE/dx particle identification. Outside this detector is a Ring Imaging Cerenkov (RICH) detector, providing excellent separation of π, K, p. Muon chambers round out the subsystems, providing μ detection above momenta around 1.5 GeV. This detector sits on the CESR accelerator, which provides electron positron collisions near $E_{CM} \approx 10GeV$, with symmetric beam energies. CLEO III has the world's largest data sample for the Υ resonances below B meson threshold. There are approximately 20 million $\Upsilon(1S)$, 10 million $\Upsilon(2S)$ and 5 million $\Upsilon(3S)$ decays in the data set. CLEO III has also collected $0.42 fb^{-1}$ of data in the $\Upsilon(5S)$ region.

3. B_S Production at the $\Upsilon(5S)$

The $\Upsilon(5S)$ is above the threshold for producing B_S mesons, and should decay, among other things, to $B_S^{(*)}\overline{B}_S^{(*)}$ states. This would be an interesting place for B factories to run to investigate B_S mixing. Up to now, no experiment has reported the observation of B_S production in Υ decays - observation and measurement of this would be an invaluable input to planning for B_S production at the B factories.

An elementary estimation leads to the hypothesis that the B_S meson decays to final states with a D_S with a branching fraction of $92 \pm 11\%$. Non strange B meson decays contain far fewer D_S mesons. Thus CLEO maps out the production of D_S mesons in the $\phi\pi$ final states as a function of D_S meson beam energy scaled momentum using off resonance and on resonance $\Upsilon(4S)$ data, and on resonance $\Upsilon(5S)$ data. The $\Upsilon(4S)$ off and on resonance yields are then scaled to the $\Upsilon(5S)$ energies, to account for continuum and non strange B meson production of the D_S, which is then subtracted from the observed spectrum. The remainder is attributed to the decay of B_S mesons to the D_S, allowing us to observe for the first time the production of the B_S at the $\Upsilon(5S)$, and quote: $Br(\Upsilon(5S) \to B_S^{(*)}\overline{B}_S^{(*)}) = 16.0 \pm 2.6 \pm 6.3\%$. This work is now published in [3].

A second search attempts to identify exclusive B_S final state. CLEOIII searched for the B_S final states $\psi\phi$, $\phi\eta$, $\psi\eta'$ and $D_S^{(*)}\pi^-$, $D_S^{(*)}\rho^-$. In a plane defined by the difference in energy between the beam energy and the final state particle energy versus the beam constrained mass of the final states, kinematics dictate a separation of the $B_S\overline{B}_S$, $B_S\overline{B}_S^*$, and $B_S^*\overline{B}_S^*$ states. CLEO III observes a preponderance of events in the ψX and $D_S^{(*)}X$ modes in the $B_S^*\overline{B}_S^*$ region. This indicates that the $B_S^*\overline{B}_S^*$ dominates the decay of the $\Upsilon(5S)$ as expected in the Unitarized Quark Model [5]. Results from this work are detailed in [4].

4. Υ Decays to Two Leptons

The decay of the $\Upsilon(nS)$ (n=1,2,3) to two leptons is interesting because it is a probe of the coupling of two b quarks to a virtual photon. As such it can be used as a test bed for LQCD [6]. In addition, this simple decay is a good place to test lepton universality by comparing the final states ee, $\mu\mu$, $\tau\tau$. Phase space corrections should be very small, and thus branchings fractions to these states should be equal. A deviation from this expectation could be a manifestation of new physics [7]. The decays of the $\Upsilon(1S)$ to lepton pairs are currently measured at the 2 to 5% level. The $\Upsilon(2S)$ decays to the ee and $\mu\mu$ final states are also measured to approximately 8%, while the $\tau\tau$ final state is known only to within 100%. For the $\Upsilon(3S)$, only the $\mu\mu$ final state is well know to an error of 10%, while the ee mode is known to exist (through the production of the 3S at colliders) and the $\tau\tau$ mode has not been observed.

5. Analysis of $\Upsilon \to \tau\tau$

The analysis of the decay $\Upsilon \to \tau\tau$ follows the method used in the analysis of the $\Upsilon \to \mu\mu$ decay[8]. The data on and off resonance for the n=1,2,3 $\Upsilon(nS)$ states are skimmed for two track events and selection criteria are tuned using data from the $\Upsilon(4S)$ to isolate both the $\mu\mu$ and $\tau\tau$ final states (τ leptons decay to final states containing one charged track approximately 75% of the time.) The off resonance data are scaled according to luminosity and beam energy (to account for background evolution) and subtracted from the on resonance data. The excess is attributed to Υ decays. The ratio of the $\tau\tau$ and $\mu\mu$ sample, in which interference between on and off resonance production cancels, provides, after efficiency correction, for a direct test of lepton universality. In addition, this method allows as a cross check the verification that the decay of the $\Upsilon(4S)$ to these final states does not occur (at our level of sensitivity.) Clear excesses of events are observed in both $\mu\mu$ and $\tau\tau$ modes at the $\Upsilon(nS)$, n=1,2,3, and no excess is observed at the $\Upsilon(4S)$. The observed event yields in both final states are corrected for efficiency, and, for the 2S and 3S, cascade decays to lower Υ states, with reasonable assumptions for unmeasured decays. The interference corrected number of $\mu\mu$ events is in perfect agreement with our previous measurement of $Br(\Upsilon \to \mu\mu)$, and in addition, the off resonance production of $\mu\mu$ and $\tau\tau$ final states is in complete agreement with the Standard Model expectation. The result of the analysis is that $R = Br(\Upsilon \to \tau\tau)/Br(\Upsilon \to \mu\mu)$ is measured as follows:

$$R(1S) = 1.06 \pm 0.02 \pm 0.00 \pm 0.03 \tag{5.1}$$

$$R(2S) = 1.00 \pm 0.03 \pm 0.12 \pm 0.03 \tag{5.2}$$

$$R(3S) = 1.05 \pm 0.07 \pm 0.05 \pm 0.03 \tag{5.3}$$

where the quoted errors are due to statistics, cascade modeling and other systematics, respectively. The systematic errors for this preliminary result are quite conservative and should decrease in the course of the analysis. This is a first observation of the decay $\Upsilon(3S) \rightarrow \tau\tau$ at the 10 σ statistical level, and is a marked improvement in the error on the branching fraction for $\Upsilon(2s) \rightarrow \tau\tau$. Note that although this result does seem to agree with the expectations from lepton universality, the deviation in a model such as that proposed by [7] in which the Υ might occasionally radiatively decay to an η_b, which then decays via a (non-standard) Higgs, will be sensitive to the energy of the photon. The efficiency for seeing the final $\tau\tau$ state will be lower in this scenario because of the extra photon, and will dilute the power of the result reported here, depending on the photon energy.

6. Dielectron Width of the Υ

The dielectron width of the Υ probes the coupling of the $b\overline{b}$ system to the electron-positron system. Ratios of these width among the different Υ states are of interest to those who study LQCD as a probe of the quark anti-quark wave function overlap as these should be calculable. The direct measurement of the production of e^+e^- in Υ decay is hindered by the large background due to Bhabha scattering that must be substracted in a direct analysis. At CLEO, the time inverted process can be measured by measuring the line shape for the production of Υ as a function of the center of mass energy of electron positron collisions. The total area of this line shape is the desired width. The observed line shape is a convolution of several components, including the inherent width Γ_{ee} ($\approx 1keV$) , the accelerator beam energy spread ($\approx 4MeV$), and the effects of initial state radiation, which also provides a non Gaussian smearing on the order of MeVs. The initial state radiation function smears the observed line shape assymetrically, giving a large tail on the high end of $s^{1/2} = E_{CM}$. The method used in this scan over the $\Upsilon(nS)$, n=1,2,3 involved weekly scans over the resonances, including off resonance points 20 MeV below the resonance peak to gauge continuum backgrounds. In order to probe the stability of the beam energy measurement, in each scan, the point with the largest slope with respect to $s^{1/2}$ was revisited. The selected events were hadronic, as these provided large well understood triggering and reconstruction efficiencies. The line shape was fit to a $1/s$ shape to account for continuum hadron production, as well as the convoluted Υ line shape. Included in this fit was an estimation of the contribution due to the interference of the continuum hadron production with Υ production. The number of events observed was corrected for efficiency, τ pair feedthrough, as well as for the far smaller contribution due to cosmic rays and beam gas collisions. The efficiency correction included a correction for the effective invisible width due to both trigger inefficiency and real physics, as estimated using the cascade $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$, and Monte Carlo simulations. The resulting preliminary fits measure the widths to be:

$$\Gamma_{ee}(\Upsilon(1S)) = 1.336 \pm 0.009 \pm 0.019\, keV \tag{6.1}$$

$$\Gamma_{ee}(\Upsilon(2S)) = 0.616 \pm 0.010 \pm 0.009\, keV \tag{6.2}$$

$$\Gamma_{ee}(\Upsilon(3S)) = 0.425 \pm 0.009 \pm 0.006\, keV \tag{6.3}$$

The errors in the above are statistical and systematic. The systematic error includes a 1.3% error due to the knowledge of the luminosity. The ratios that are of direct relevance to LQCD are:

$$\frac{\Gamma_{ee}(\Upsilon(2S))}{\Gamma_{ee}(\Upsilon(1S))} = 0.461 \pm 0.008 \pm 0.003 \tag{6.4}$$

$$\frac{\Gamma_{ee}(\Upsilon(3S))}{\Gamma_{ee}(\Upsilon(1S))} = 0.318 \pm 0.007 \pm 0.002 \tag{6.5}$$

$$\frac{\Gamma_{ee}(\Upsilon(3S))}{\Gamma_{ee}(\Upsilon(2S))} = 0.690 \pm 0.019 \pm 0.006 \tag{6.6}$$

7. Direct Photons in Υ Decays

Below B meson threshold, two important channels in Υ decay are the three gluon ggg and the γgg exchange diagrams. The photon in the γgg process escapes into the detector, and thus is a direct witness of the physics of the $b\overline{b}$ overlap. The ratio of the number of events observed in these two processes $R_\gamma = N(\gamma gg)/N(ggg)$ is a function of the strong and electromagnetic coupling, as well as the charge of the b quark, and can be used to gauge the relative importance of these two processes. The search proceeds by tabulating hadronic events with an isolated high energy photon reconstructed in CLEO. The energy spectrum of the photon is used to untangle the physics from the backgrounds. Continuum processes are subtracted by an off resonance subtraction. The two main backgrounds are photons that come from ISR, which are the dominant background at the highest photon energy, while at lower energies the dominant background comes from photons resulting from π^0 decays. The ISR background is expected to be reasonably well simulated by the event simulation. The background due to π^0's comes from complicated physics processes, and one might question the veracity of a Monte Carlo model. To circumvent this, CLEO uses a data driven Monte Carlo : using the reconstructed spectrum of charged pions, we can predict the spectrum of real π^0, and then throw Monte Carlo π^0's that reproduce this spectrum. These π^0's are then allowed to simulate the real background process. The ISR and π^0 derived background are subtracted from the continuum subtracted on resonance data, and the resulting distribution is fit to a sum of two contributions. The first represents the mismatch of our subtraction at low photon energies, while the second component is the distribution expected for the direct photons. We fit to two models [9][10], both of which expect a predominance of photons at higher energies. These models are derived for the $\Upsilon(1S)$ but lacking other suitable models, we also apply them to the $2S$ and $3S$ states. The fits for the higher resonances include the effects of cascades to lower resonances. In the ratio for R_γ, the denominator is determined from the known number of Υ in the CLEO dataset, as well input from the PDG[1] and Monte Carlo simulations. The preliminary results are: $R_\gamma(1S) = 2.90 \pm 0.007 \pm 0.22 \pm 0.15\%$, $R_\gamma(2S) = 3.49 \pm 0.03 \pm 0.58 \pm 0.18\%$, and $R_\gamma(3S) = 2.88 \pm 0.03 \pm 0.38 \pm 0.12\%$ where the errors are statistical, systematic and model dependence. The systematic error is dominated by the π^0 photon feedthrough model. The value of $R_\gamma(1S)$ is consistent with previous values, and has similar systematic errors, but smaller statistical errors. This is the first measurement of $R_\gamma(2S)$ and $R_\gamma(3S)$.

8. The Decay $\Upsilon(1S) \to h^+h^-\gamma$

The radiative decays of the $\Upsilon(1S)$ can be used to probe the 2 gluon structure. There are many interesting results from J/ψ decays, including the observation of tensor states $f_2(1270)$ [11, 12, 13, 14] and $f_2'(1525)$ [15, 16], the claim of a glueball candidate known as the $f_j(2220)$ [17], and the observation of a $p\overline{p}$ near threshold enhancement termed the $X(1860)$ [18]. In the $\Upsilon(1S)$ system, one might hope to observe similar effects suppressed by a factor due to the relative quark charge and the quark mass for the propagator, squared, which roughly predicts rates reduced by a factor of 1/40. In this analysis, CLEO searches for the final state $h^+h^-\gamma$ in $\Upsilon(1S)$ decays, by requiring a bachelor photon of energy greater than 4 GeV. The $h^\pm$ are identified as π, K or p by combining dEdx and RICH information. In addition, the knowledge of the total beam energy is used as an extra input to test for PID hypothesis consistency. Continuum decays are accounted for by subtracting suitably scaled off resonance data. The resulting 2 body mass spectra reveal a clear $f_2(1270)$ in the $\pi\pi$ spectrum, as well as a clear $f_2'(1525)$ in the KK spectrum. No clear structure is observed in the $p\overline{p}$ spectrum. No evidence for the $f_j(2220)$ is observed in any of the spectra. There is an unexplained broad excess of events in the KK mass distribution above 2 GeV. In addition, there is no evidence of the $X(1860)$ in the $p\overline{p}$ spectrum. The decay angles are fit and it is confirmed that the $f_2(1270)$ and the $f_2'(1525)$ are spin 2 objects decaying predominantly with helicity 0. Preliminary branching ratios are: $Br(\Upsilon(1S) \to \gamma f_2(1270)) = 10.2 \pm 0.8 \pm 0.7 \times 10^{-5}$ and $Br(\Upsilon(1S) \to \gamma f_2'(1525)) = 3.7^{+0.9}_{-0.7} \pm 0.8 \times 10^{-5}$. The excess in the KK spectrum for $2GeV < m_{KK} < 3GeV$ is $Br(\Upsilon(1S) \to \gamma K^+K^-) = 1.14 \pm 0.08 \pm 0.10 \times 10^{-5}$. Upper limits at 90% C.L. are set at: $Br(\Upsilon \to \gamma f_2(980)) < 3 \times 10^{-5}$, $Br(\Upsilon \to \gamma f_2(2050)) < 0.6 \times 10^{-5}$, $Br(\Upsilon \to \gamma f_0(1710)) < 0.7 \times 10^{-5}$. For the mass region $2GeV < m_{p\overline{p}} < 3GeV$, $Br(\Upsilon(1S) \to \gamma p\overline{p}) < 0.6 \times 10^{-5}$. Additional limits on the branching fraction to the $f_j(2220)$ and the $X(1860)$ are set at the 10^{-6} level. The branching fractions for the $f_2(1270)$ and $f_2(1270)$ are consistent with the naive expectation derived from J/ψ decays. It is not clear that any of the other results are in conflict with this scaling. The results of this work can be found in [19]. An additional analysis is underway looking for final states including a photon and $\pi^0\pi^0$, $\eta\eta$, and $\pi^0\eta$.

9. Observation of $\chi_b(2P) \to \chi_b(1P)\pi^+\pi^-$

The transition of $\chi_b(2P) \to \chi_b(1P)\pi^+\pi^-$ is observed in an electromagnetic decay of the $\Upsilon(3S)$ to the $\chi_b(2P)$ followed by the dipion transition down to the $\chi_b(1P)$ followed by a electromagnetic transition down to the $\Upsilon(1S)$. The $\Upsilon(1S)$ is then observed by its decay to ee or $\mu\mu$. The final state, excluding the leptons, consists of 2 charged pions and 2 photons, which is also the final state of the chain $\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$, $\Upsilon(2S) \to \chi_b\gamma$, $\chi_b \to \Upsilon(1S)\gamma$. This measured background with slightly different photon energies and dipion mass can be used to gauge the correctness of the analysis of the sought after transition. Other backgrounds exist but require the loss of at least 1 photon, and are thus somewhat suppressed. The analysis plots the energy of largest energy photon against the inferred mass of the dipion system. Two analyses were pursued. The cascade pions tend to have low momentum, and thus, reconstruction of both of them tends to have low efficiency. The Di-pion analysis attempts to reconstruct both pions. In this analysis, the $\Upsilon(2S)$ contamination is found to be consistent with expectation, and 7 events are observed in the signal region over a background of 1.2 expected events. The efficiency for this analysis is $\varepsilon = 4.5\%$. The single pion analysis sees 17 events, over an expected background of 3.3 events, with an efficiency of $\varepsilon = 8.5\%$. The two analyses see consistent results and can be combined to give a 6 σ significant observation. CLEO thus reports the first observation of a dipion transition outside of a $^3S_1$ system, and a preliminary width of $\Gamma(\chi_b(2P) \rightarrow \chi_b(1P)\pi^+\pi^-) \approx 0.9keV$. Further details can be found in [20].

10. Conclusions

This talk has highlighted results from the Υ analyses at CLEOIII. CLEO has made the first observation of B_S production in $\Upsilon(5S)$ decays. CLEO has also for the first time observed the decay $\Upsilon(3S) \rightarrow \tau\tau$, and obtained precision results on the ratio of the $\tau\tau$ width to the $\mu\mu$ width in $\Upsilon(nS)$ decay, n=1,2,3. A measurement of the dielectron width of the $\Upsilon(nS)$ n=1,2,3 was also presented. Direct photon measurements in hadronic Υ decays presented here shed light on the relative importance of γgg and ggg intermediate states in Υ decays. The substructure of the hadrons in the $\Upsilon(1S) \rightarrow \gamma h^+h^-$ decays was determined to be consistent with the extrapolated expectation from $J\psi$ decays. A broad enhancement in the KK channel was observed, and no evidence was seen for the $f_j(2220)$ or the $X(1600)$. The first observation of the dipion transition between the $\chi_b(2P)$ and the $\chi_b(1P)$ was also presented. All results presented in this talk are preliminary unless otherwise noted.

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